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ORIGINAL CONTRIBUTION

Evaluation of Lane-Based Traffic Characteristics of Highways Under Mixed Traffic Conditions by Different Methods

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Abstract Many researchers have concentrated on analyzing the traffic characteristics of the highway segments as a whole rather than considering individual lanes. Hence, in the present study, a comparison of the lane-based vehicle speeds and estimation of lane-based Dynamic Passenger Car Unit (DPCU) is carried out. Later, the estimated DPCU values for vehicles on Median Lane (ML) and Kerb Lane (KL), as well as the entire roadway (RW), are compared with the Indo-HCM:2017, and IRC-64:1990 suggested DPCU and PCU values, respectively. An enormous amount of traffic-related field data was collected using the infra-red sensor technique at the different highway mid-block sections in India. The macroscopic fundamental relationship diagrams among speed, flow, and density under different highway lanes such as ML and KL, and the RW, are established using the Greenshields Linear Model to determine the lane-based (ML and KL) and RW capacity. The study results reveal that the capacity estimated using the Indo-HCM:2017 and IRC-64:1990 suggested DPCU and PCU values, respectively, overestimated the lane-based capacity but underestimated the RW capacity compared to the capacity estimated using the DPCU values in this study. The analysis results also show a distinct difference between speed and DPCU values for the vehicles in different lanes and RW. Hence, proving that the assumption and use of RW speed, DPCU, and capacity values without considering the individual lanes as erroneous. The findings from this study emphasize the importance of taking lane-based characteristics into account rather than complete RW characteristics, thus addressing significant shortcomings in the previous studies.

Keywords Lane-based capacity · Dynamic passenger car unit (DPCU) · Mixed traffic · Uninterrupted highway facility · Infra-Red (IR) sensor detector

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Introduction

Understanding the lane-based traffic characteristics is essential for designing highways, modeling traffic operations, and assessing the performance of uninterrupted highway facilities. Mixed traffic (i.e., plying of different vehicle types) is encountered in Indian highways with vehicles having diverse physical and operational characteristics. For an uninterrupted highway facility with multiple lanes under mixed traffic conditions, the vehicle's lane position is considered a critical factor influencing traffic stream characteristics and performance. For this reason, while analyzing the highway's capacity, the lane-based speed-flow characteristics need to be considered. A more precise measurement of lane-based traffic characteristics would provide the real-field highway speed and capacity values. Moreover, highway capacity estimation is highly concerned with the number of lanes and lane position since flows are distributed unequally between lanes [1].

Most traffic studies have assumed average highway capacity per lane as equal, neglecting the lane-based performance. This is reasoned to be due to the complexity and heterogeneity involved in the Indian traffic environment. However, traffic studies have shown that increasing the number of lanes or the width of lanes increases the average highway capacity per lane [2]. Moreover, the authors believe that it is worth departing from the erroneous practice of averaging traffic characteristics on all lanes instead of measuring individual lane characteristics to understand better what is happening on the individual lanes of the highway. Like the speed, time-headway, and space-headway, the other traffic characteristics are also not similar for different highway lanes. As the estimated Passenger Car Unit (PCU) for vehicles is non-lane-based, the estimated capacity is also non-lane-based. Even the microscopic simulation models build without considering the lane-based characteristics give unrealistic results. This disparity in the non-lane-based consideration of traffic characteristics underlines the need for this research to understand lane-based traffic behavior under mixed traffic conditions. Thus, the present study was undertaken with an aim, first, to evaluate the differences in speed of vehicles on individual lanes incorporating the traffic heterogeneity observed in Indian highways, second, to estimate the lane-based Dynamic PCU (DPCU) values for each vehicle class based on the speed-area ratio method, and compare with the Indian Highway Capacity Manual (Indo-HCM:2017) [3] and Indian Road Congress (IRC-64:1990) [4] recommended values. Third, to determine the lane-based and RW highway capacity, and compare the capacity values with the one estimated by the Indo-HCM (2017) [3] and IRC:64 (1990) [4] methods.

Background Literature

The PCU factors for rural highways recommended in the existing code of practice–IRC:64 (1990) [4] are constant. These values do not perform well by not involving the real-field vehicle dynamicity of mixed traffic. Therefore, Chandra and Sikdar [5] proposed the DPCU concept to homogenize the mixed traffic under different roadway and traffic conditions. While DPCU is widely recognized as a homogenizing factor for Indian traffic conditions, the variation of DPCU on highway lanes remains unexplained. Furthermore, using these DPCU values in the field without any logical analysis of the real-field traffic data would be inopportune. Al-Zerjawi [6] applied the ratio of the density of passenger cars to the density of trucks for determining the truck PCU values on the multilane highways. Tiwari et al. [7] used a modified density method to estimate the vehicle PCU values on divided highways in India. The modified density approach considered the loose lane discipline of the heterogeneous highways. These studies did not focus on evaluating the lane characteristics of the traffic stream.

There have been several attempts to develop theoretical traffic models, which include the Greenshields linear model [8], the Greenberg logarithmic model [9], the Underwood exponential model [10], including the Van Aerde single regime model [11], the Edie multi-regimes model [12], the Drake multi-regime model [13], and the Drew parabolic model [14]. Nevertheless, the implications of lane-based traffic characteristics had not been sufficiently stressed in these traffic models. With no iota of doubt, it can be said that the traffic-flow parameters across different highway lanes vary significantly [15]. This variation has a considerable effect on the highway capacity because of the vehicular heterogeneity and abreast driver behavior in the mixed traffic environment.

Daganzo [16] considered two types of lanes in a freeway section. The study focused on eliminating the assumption of homogeneity for forming a system of Lighthill–Whitham–Richards (LWR) traffic-flow model [17]. Al-Kaisy et al. [18] used Queue Discharge Flow (QDF) capacity as an equivalent criterion to develop Passenger Car Equivalent (PCE) values. They found that the effect of traffic composition on PCE is significant. Hurdle et al. [19] attempted to compare the lane-based speed-flow relationships of a three-lane highway in Canada with Highway Capacity Manual (HCM-1994) curves for different free-flow speeds (60, 65, and 70 mph). The authors found that the cubic function performed reasonably well instead of the linear function for the speed-flow relationships. Velmurugan et al. [20] employed microscopic simulation technique to develop the vehicle-type-specific speed-flow model equations for Indian multilane highways. However, the implications of lane-based parameters and their effect on the fundamental diagram remain unexplored.

More recently, a study by Sasahara et al. [1] estimated the traffic speed and flow for individual lanes on the freeway, considering the respective Lane Flow Distribution (LFD) factor. In another recent study by Reina and Ahn [21], an empirical analysis of LFD in three-lane congested freeways in the U.S.A was carried out. The study investigated the flow characteristics that affect traffic behavior on lanes and found the LFD to be showing a non-uniform trend. Hence, concluding that one lane's LFD differed substantially from the other lane's LFD. Li et al. [22] carried out a comparison of three different capacity estimation methods, namely, the Saturation Flow Rate (SFR) method, HCM (2016) method, and a simulation approach. The study site considered was a two-way four-lane freeway work zone section in China, which showed that the SFR method is a reliable and alternate capacity estimation method.

The critique of the above studies reveals that only a few studies hitherto are available and have been possible until now to analyze the lane-based highway traffic

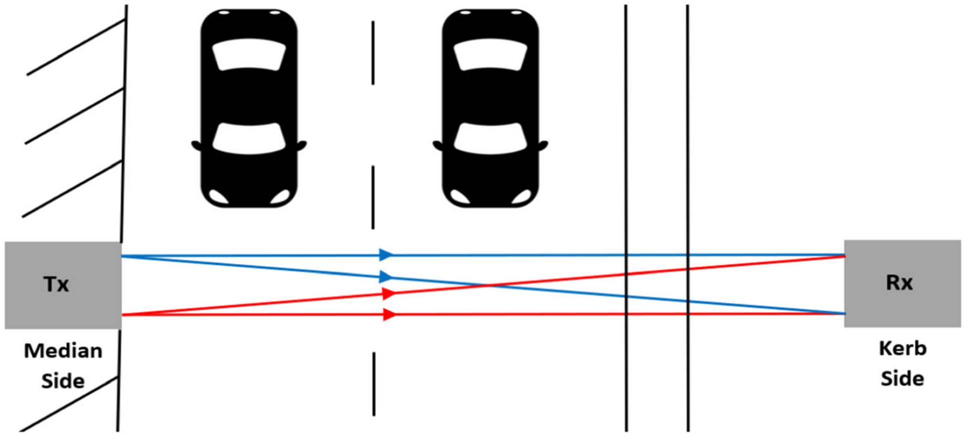


Fig. 1 Vehicle detection mechanism through the transmission of IR beams between the Tx and Rx

Fig. 2 Set up of IR sensor detector device across NH-32

Fig. 3 Set up of IR sensor detector device across NH-38

Fig. 4 Set up of IR sensor detector device across NH-83

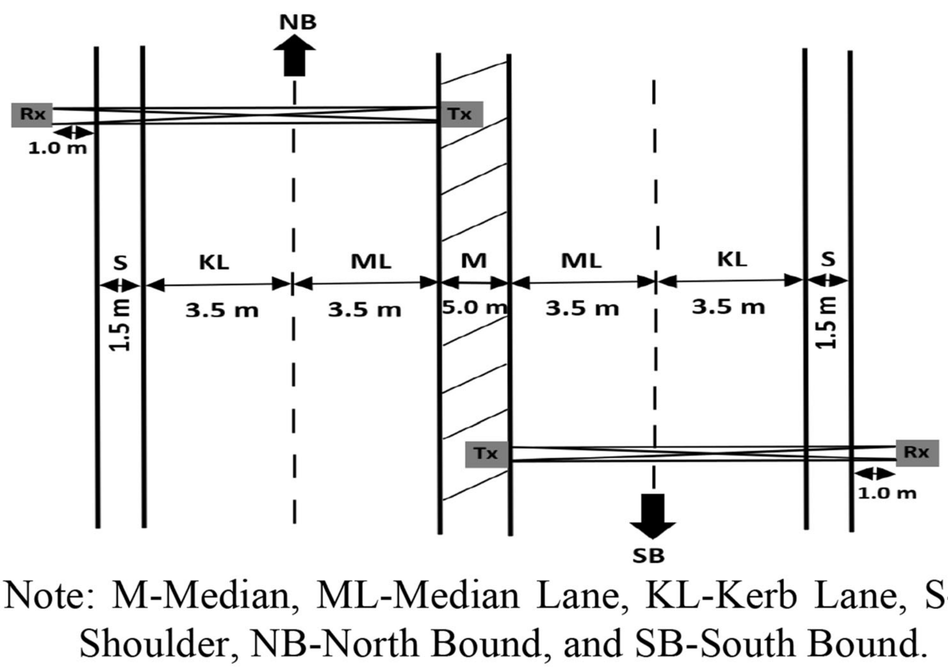


Fig. 5 Geometric layout of NH-32. *Note*: M-Median, ML-Median Lane, KL-Kerb Lane, S-Shoulder, NB-North Bound, and SB-South Bound.

characteristics, especially under Indian traffic conditions. There is no doubt that the conditions of traffic flow across various highway lanes vary considerably. Hence, this study focuses on analyzing and comparing the lane-based speed-flow-density models developed using three different methods to estimate highway capacity under mixed traffic conditions.

Study Methodology

Six different uninterrupted highway segments were considered to collect traffic data using an Infra-Red (IR) sensor-based device. Descriptive statistical analysis on the vehicle's speeds in both the lanes and the entire roadway was carried out. A z-test was used to check the difference in vehicle speeds of different lanes. The lane-based DPCU

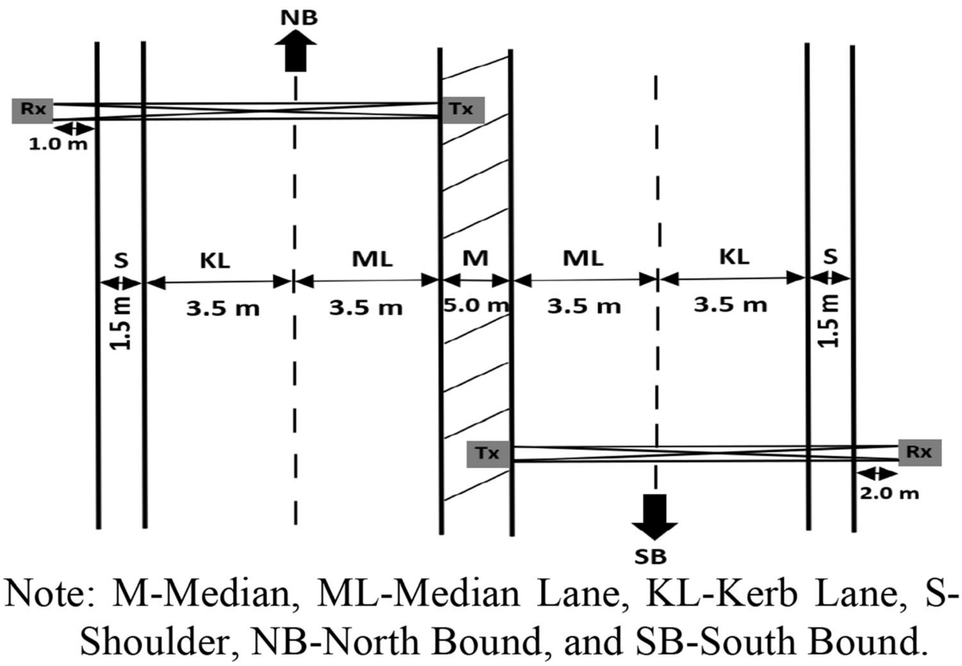


Fig. 6 Geometric layout of NH-38. *Note*: M-Median, ML-Median Lane, KL-Kerb Lane, S-Shoulder, NB-North Bound, and SB-South Bound

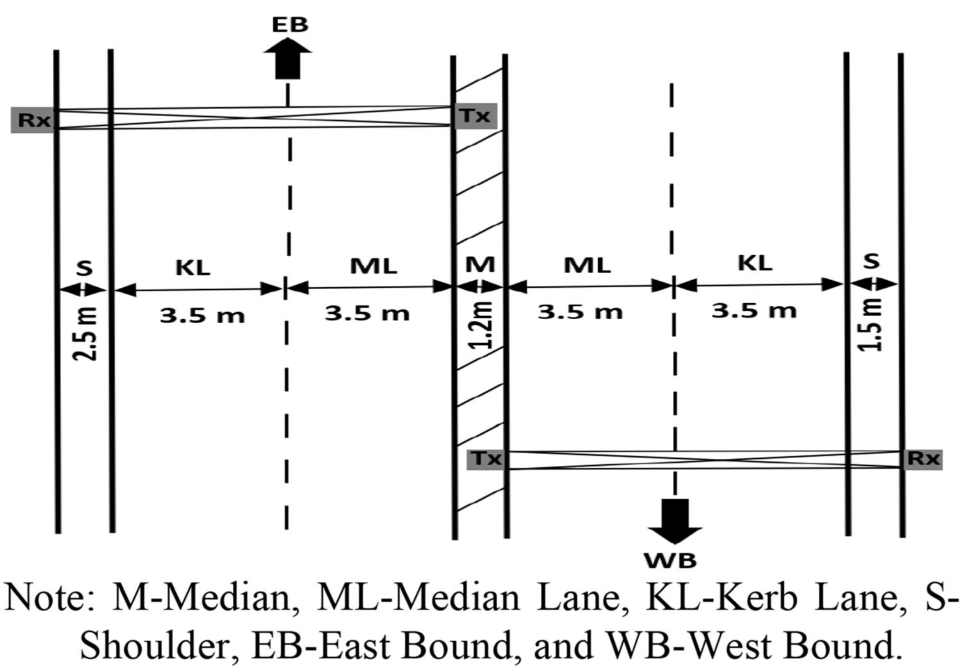


Fig. 7 Geometric layout of NH-83. *Note*: M-Median, ML-Median Lane, KL-Kerb Lane, S-Shoulder, EB-East Bound, and WB-West Bound

values of each vehicle type are determined using the speed-area ratio method and are compared with the values suggested by Indo-HCM (2017) [3] and IRC:64 (1990) [4]. Since the prior studies inadequately represent the Macroscopic Fundamental Diagrams (MFDs) without considering the lane-based characteristics, we develop the lane-based MFDs establishing the speed-flow-density relationships for every lane and roadway based on the

Table 1 Average vehicle dimensions recorded by the IR sensor device at the study sites

Vehicle class	Length (m)	Width (m)	Area (m^2)
2W	1.68	0.68	1.14
3W	2.65	1.19	3.15
CS	3.51	1.55	5.44
CB	4.85	1.65	8.00
SCV	4.75	1.22	5.80
LCV	5.55	1.62	8.99
MCV	8.79	2.10	18.46
HCV	8.88	2.24	19.89
MAV	10.15	2.33	23.65
TR	7.42	2.20	16.32
BI	1.54	0.35	0.54

single regime traffic-flow models. The lane-based and roadway capacity values determined by considering the DPCU values and estimated using the adopted speed-area ratio method are compared with the lane-based and roadway capacity values determined by considering the DPCU values and static PCU values suggested by the Indo-HCM (2017) [3] and IRC:64 (1990) [4], respectively.

Field Data Collection

The traditional methods of obtaining traffic data, such as videography, are a laborious and complicated process. This difficulty is due to the complexity and nature of mixed traffic on Indian highways. This issue can be addressed using the advanced Infra-Red (IR) sensor technology-based device such as the Transportable Infra-Red Traffic Logger (TIRTL). It can record various traffic variables like vehicle speed, headway, clearance, gap, spacing, lane-by-lane traffic count, classified traffic composition, the vehicle dimension, the number of axles of the vehicles, etc. It is also an automated, portable, and all-weather traffic data collection device that works non-intrusively with advanced functional features. These features make it the most flexible, user-friendly product in the present world of Intelligent Transportation System (ITS).

It comprises a transmitter unit (Tx) and receiver unit (Rx) positioned perpendicular to the traffic flow, in one direction or another. The Tx is the source of the IR beams and is generally placed on the median side. It is used to detect traffic. On the other hand, the Rx connected to a laptop and usually placed on the kerbside is used to detect IR beams' disruptions from vehicle wheels. When any vehicle crosses the IR sensor detection zone, the Tx unit forms two straight and two crossed IR beam pathways. The IR sensor device records two-beam events for any vehicle detection, one for the vehicle-axle entering and the other leaving the detection points—thereby recording two beams for four beam pathways. Thus, generating eight timestamped events per axle, which are used to derive the vehicle speed. These beam events are recorded for further processing by the vendor-developed intelligent software, which provides traffic data such as spacing, headway, clearance, and gap based on the relative timing of those beam-interruption events. The timestamp registered for each vehicle axle helps to establish the inter-axle spacing and the number of axles. The recorded inter-axle spacing and the number of vehicle axles are compared to a table of inter-axle spacing ranges stored in the unit to gauge the vehicle class accurately. The time difference between each parallel IR-light beam and each diagonal IR-light beam is used to correctly find the vehicle lane position and classification. Fig. 1 shows the vehicle detection mechanism by the IR sensor device.

The IR sensor device setup for traffic data collection across one of the directions of the National Highways (NH) sections, NH-32, NH-38, and NH-83, is illustrated in Fig. 2, Fig. 3, and Fig. 4, respectively. The IR sensor device, with its auto-calibration feature, does not require any manual calibration. The real-time field recorded traffic data can be viewed in the user-friendly interface, and the traffic data is stored as a .csv file in the laptop device connected to the Rx.

Accuracy of the Traffic Data Collected Using the IR Sensors

The traffic passing through the IR detection point of the IR sensor device was videotaped by placing a video camera on a sufficiently high mast, which covered a trap length of 50 m. The vehicle detection timings of both the IR sensor device and video camera are synchronized. This assured that the traffic detected by the IR sensor device was consistent with the traffic recorded by the video camera.

The recorded traffic video was reviewed in the lab; the speed and vehicle classification records were extracted manually for comparison with the IR sensor device recorded data. Comparing the extracted test results for one-hour peak traffic data from one of the highway sections showed 96% and 94% accuracy for vehicle speed and classified vehicle count, respectively. Other similar studies [24, 25] showed that a precise measurement of the speed of vehicles up to 99% [24] and classified vehicle count up to an accuracy of 94–97% [25] was possible when the IR sensor-based system was deployed on the roads. However, it was observed in the field that the performance of TIRTL is

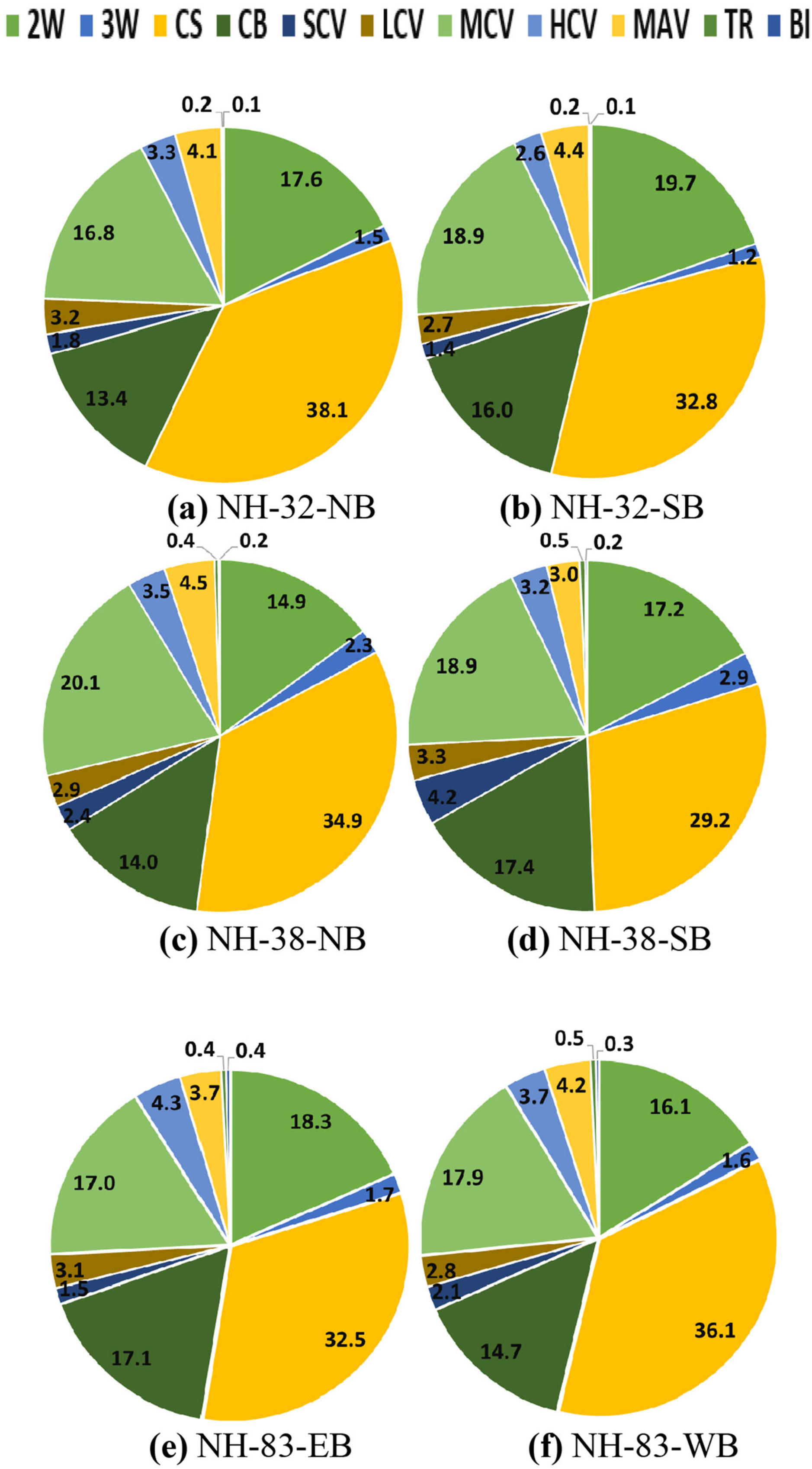


Fig. 8 Vehicular compositions at the study sites. **a** NH-32-NB **b** NH-32-SB, **c** NH-38-NB **d** NH-38-SB, **e** NH-83-EB **f** NH-83-WB

Table 2 Summary statistics of the speeds of vehicles (Kmph) in ML, KL, and RW

Vehicle class	Mean			Std Dev			CV			15th %ile			50th %ile			85th %ile		
	ML	KL	RW	ML	KL	RW	ML	KL	RW	ML	KL	RW	ML	KL	RW	ML	KL	RW
2W	52	48	50	11	14	13	21	29	25	24	20	22	54	46	50	71	68	70
3W	47	42	45	17	14	16	36	33	35	20	18	19	50	40	45	58	55	57
CS	82	80	81	11	19	15	13	24	19	29	24	27	80	77	79	88	85	87
CB	85	78	82	13	15	14	15	19	17	31	25	28	84	76	80	90	88	89
SCV	54	51	53	12	16	14	22	31	27	20	18	19	52	49	51	68	65	67
LCV	71	62	67	19	14	17	27	23	25	24	22	23	70	61	66	78	74	76
MCV	63	60	62	07	09	08	11	15	13	27	25	26	64	58	61	69	66	68
HCV	52	50	51	14	16	15	27	32	29	25	18	22	54	49	52	62	58	60
MAV	46	44	45	06	11	09	13	25	19	19	16	18	48	43	46	63	55	59
TR	30	28	29	14	19	17	47	68	57	16	15	16	29	26	28	35	32	34
BI	25	22	24	04	07	06	16	32	23	15	14	15	24	20	22	29	26	28

precisely possible by maintaining a proper balance between the alignment of Tx and Rx for accurate IR beam transmission.

Geometric Details of the Study Sites

The mid-block portion of the NHs in Tamil Nadu, India, was selected as the study site. These sites were chosen to meet the base condition criteria requirements recommended by the Indo-HCM (2017) [3].

The study sections are free from any kind of horizontal curvature and vertical gradient, physical barriers like rumble strips and speed breakers, including a transfer station, pedestrian movement area, and central divider openings. The sections are also free of interference from upstream or downstream intersections nearby, ensuring a minimum side friction effect on the flow of vehicles. The layout showing the geometric details of the study sites, NH-32, NH-38, and NH-83, are illustrated in Figs. 5, 6, and 7, respectively.

The IR sensor system installed over each direction of the four-lane divided highway collected the lane-based traffic data. The acquisition of traffic data was carried out for 24-hours at each of the highway sections. However, traffic data varying between 16–24 hours was extracted from each highway section to achieve nearly equal traffic composition of all vehicles at every highway section. The traffic speed and volume counts are extracted at five-minute aggregation to develop the speed-flow-density models for each lane (Median Lane-ML and Kerb Lane-KL) and roadway (RW) using the MFDs.

Table 3 Statistical results for the speed of vehicles in ML and KL: z-test results

Vehicle class	Observed z-value	Critical z-value	Significant speed difference
2W	3.36	1.96	Yes
3W	3.47	1.96	Yes
CS	4.54	1.96	Yes
CB	2.71	1.96	Yes
SCV	3.42	1.96	Yes
LCV	4.85	1.96	Yes
MCV	3.27	1.96	Yes
HCV	5.47	1.96	Yes
MAV	2.28	1.96	Yes
TR	4.13	1.96	Yes
BI	2.54	1.96	Yes

Vehicle Classification and Composition

The total traffic was classified into eleven different vehicle categories, such as 2-Wheeler (2W), 3-Wheeler (3W), Standard/Small Car (CS), Big Car (CB), Small Commercial Vehicle (SCV), Light Commercial Vehicle (LCV), Medium Commercial Vehicle (MCV), Heavy Commercial Vehicle (HCV), Multi Axle Vehicle (MAV), Tractor (TR) and Bi-cycle (BI). Table 1 represents the recorded physical dimensions of the vehicle, such as length, width, and area.

The cars with a physical area of more than 5.44 m^2 are considered CB, and the rest are considered CS. The SCV and LCV included small-sized commercial goods vehicles

Table 4 Estimated DPCU values for different vehicle types and their comparison with Indo-HCM (2017) and IRC:64 (1990) values

Vehicle class	Vehicle speed (kmph)			Vehicle area (m^2) a_i	Estimated DPCU values			Indo-HCM (2017) DPCU value		IRC:64 (1990) Static PCU values
	ML	KL	RW		ML	KL	RW	Range	Median	
2W	52	48	50	1.14	0.33	0.35	0.34	0.3–0.5	0.40	0.5
3W	47	42	45	3.15	1.01	1.10	1.05	1.1–1.3	1.20	1.6
CS	82	80	81	5.44	1.00	1.00	1.00	–	1.00	1.0
CB	85	78	82	8.00	1.42	1.51	1.46	1.4–1.5	1.45	–
SCV	54	51	53	5.80	1.62	1.67	1.64	–	–	–
LCV	71	62	67	8.99	1.91	2.13	2.01	2.7–3.3	3.10	2.8
MCV	63	60	62	18.46	4.42	4.52	4.47	3.5–4.6	4.40	4.5
HCV	52	50	51	19.89	5.77	5.85	5.81	3.5–4.6	4.40	4.5
MAV	46	44	45	23.65	7.75	7.90	7.83	6.3–7.0	6.60	6.0
TR	30	28	29	16.32	8.20	8.57	8.38	3.9–7.0	6.20	4.5
BI	25	22	24	0.54	0.33	0.36	0.34	–	–	0.6

Table 5 Model equations and R^2 values from different traffic stream models

Highway Section	GLM (Model equation, R^2 value)	GBM (Model equation, R^2 value)	UWM (Model equation, R^2 value)
NH-32-NB	$v = 80.20–0.5547*k$	$v = 122.41–13.787*\ln(k)$	$v = 83.81*e^{-0.0035*k}$
	0.967	0.905	0.929
NH-32-SB	$v = 82.14–0.5460*k$	$v = 128.36–12.341*\ln(k)$	$v = 85.34*e^{-0.0030*k}$
	0.956	0.894	0.938
NH-38-NB	$v = 77.52–0.4766*k$	$v = 98.65–8.347*\ln(k)$	$v = 80.08*e^{-0.0041*k}$
	0.985	0.899	0.943
NH-38-SB	$v = 71.70–0.4844*k$	$v = 93.28–11.365*\ln(k)$	$v = 72.28*e^{-0.0056*k}$
	0.972	0.897	0.937
NH-83-EB	$v = 75.36–0.5074*k$	$v = 96.30–9.137*\ln(k)$	$v = 77.39*e^{-0.0046*k}$
	0.989	0.935	0.976
NH-83-WB	$v = 73.18–0.5081*k$	$v =94.58–10.838*\ln(k)$	$v = 74.79*e^{-0.0052*k}$
	0.961	0.921	0.959

v = Traffic speed; and k = Traffic density

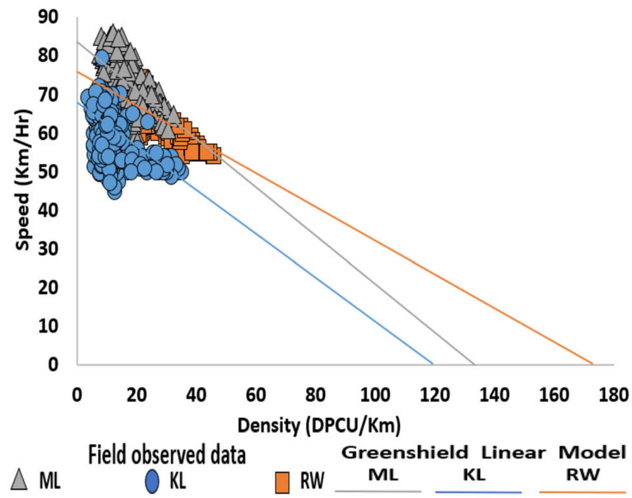
and light-weight commercial goods vehicles, respectively. The MCV included 2-Axle Rigid Trucks/

Buses, while the HCV included 3-Axle Rigid Trucks/ Buses. All other commercial vehicles with 4-axles, 5-axles, and 6-axles were considered as MAV. The traffic compositions observed in all the six NH locations were extracted. The compositional share of the vehicle classes for NH-32-NB, NH-32-SB, NH-38-NB, NH-38-SB, NH-83-EB, and NH-83-WB are illustrated in Figs. 8 a, b, c, d, e, and f, respectively.

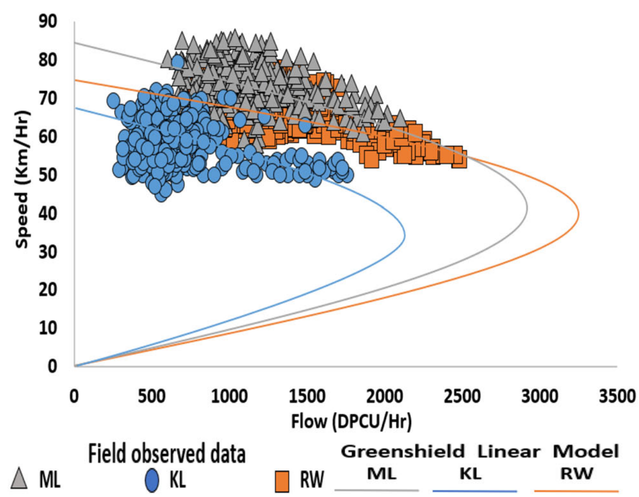
Lane-Based Speed Data Analysis

Descriptive Statistics of Vehicle Speeds (ML and KL)

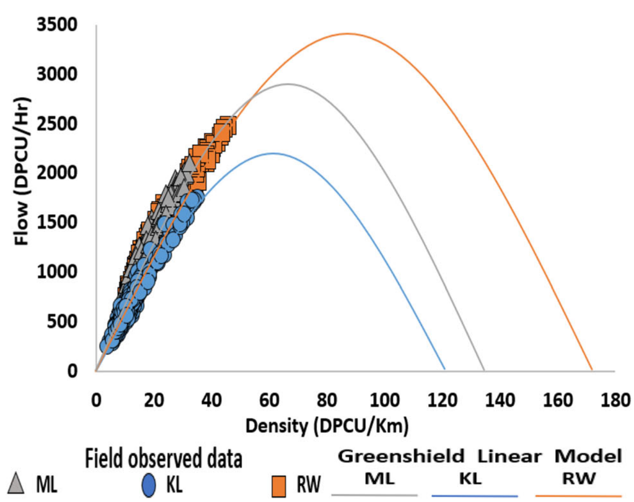
The descriptive statistical analysis of the vehicle speeds shows a wide variation in ML and KL. This speed variation was observed due to their physical and operational characteristics. The TIRTL recorded the spot speed of the traffic. However, during the five-minute aggregation, the harmonic mean of the vehicle speed is considered, which represented the Space Mean Speed (SMS) of the traffic. The summary statistics of speed parameters for the



(a) v-k plot



(b) v-q plot



(c) q-k plot

Fig. 9 Macroscopic fundamental relationship diagrams by the speed-area ratio method. **a** v-k plot, **b** v-q plot, **c** q-k plot

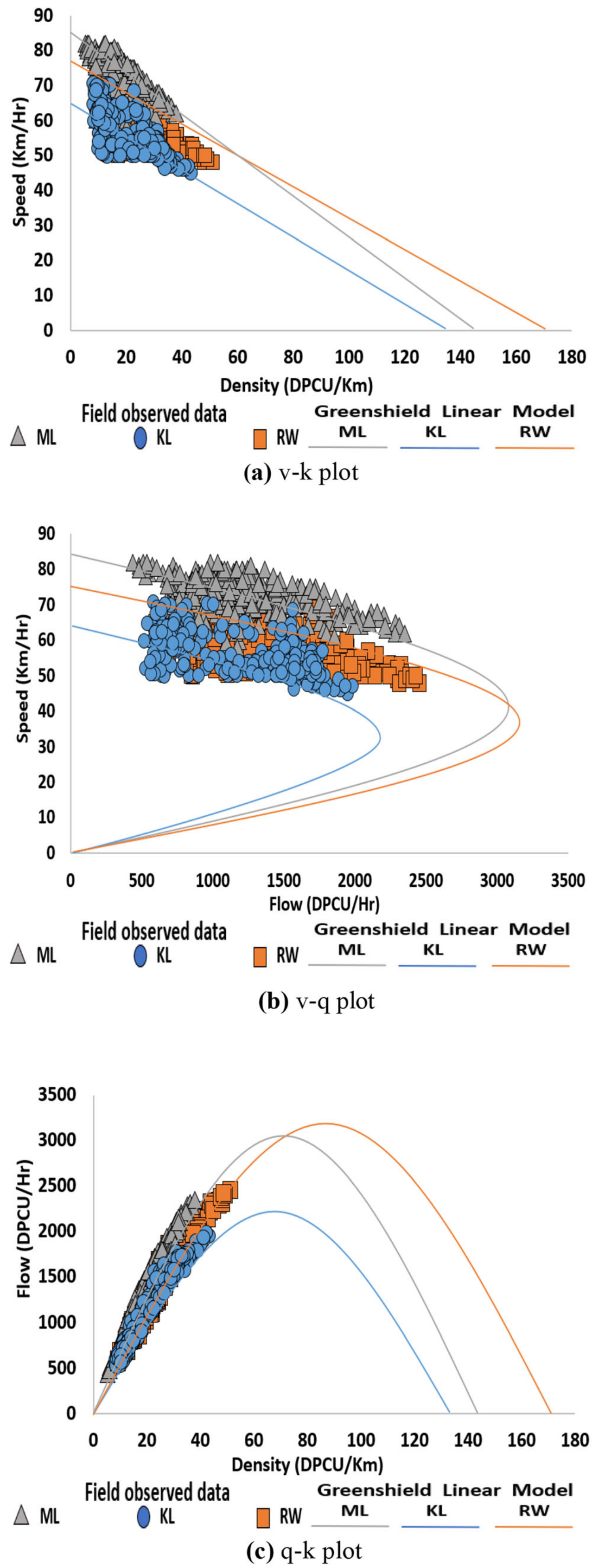
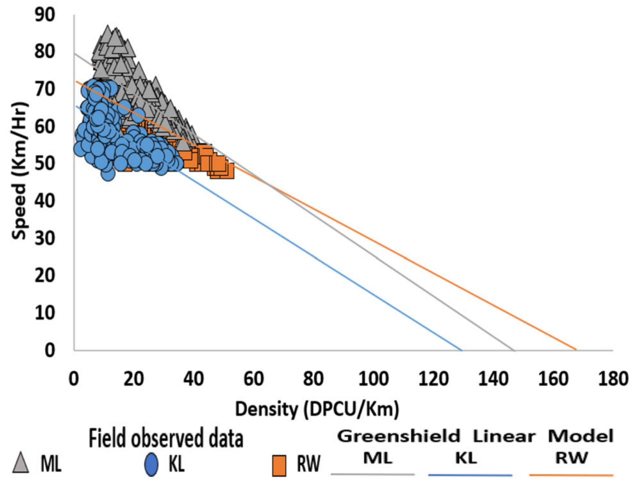
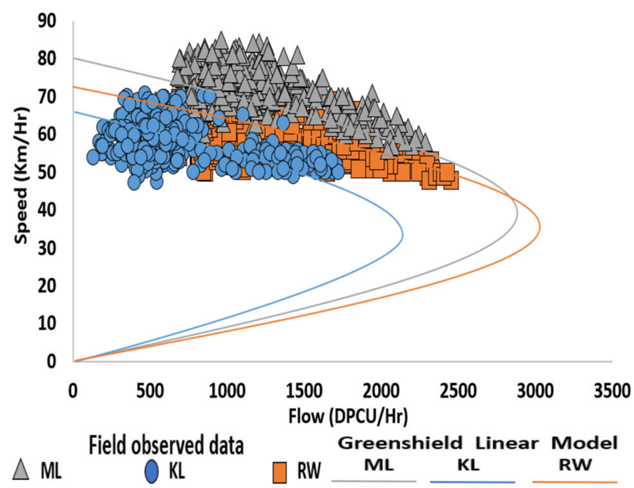


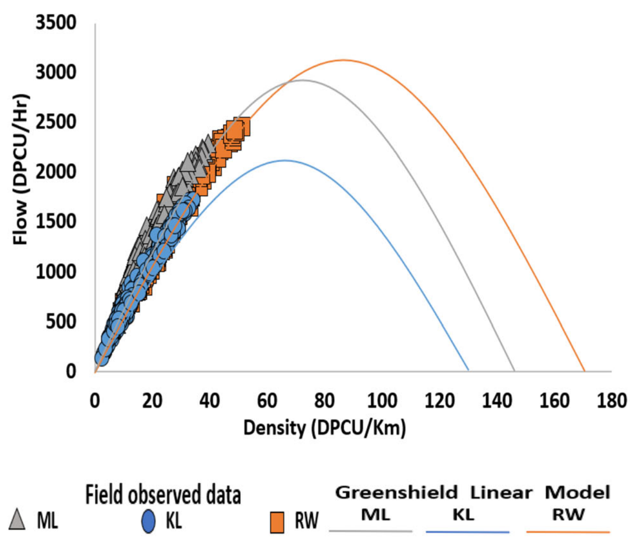
Fig. 10 Macroscopic fundamental relationship diagrams by the Indo-HCM (2017) method **a** v-k plot, **b** v-q plot, **c** q-k plot



(a) v-k plot



(b) v-q plot



(c) q-k plot

Fig. 11 Macroscopic fundamental relationship diagrams by the IRC:64 (1990) method **a** v-k plot, **b** v-q plot **c** q-k plot

Table 6 Traffic parameters by the Speed-Area ratio, Indo-HCM (2017) and IRC: 64 (1990) methods

Traffic parameter	Speed-Area ratio method			Indo-HCM (2017) method			IRC:64 (1990) method		
	ML	KL	RW	ML	KL	RW	ML	KL	RW
Free-flow speed (V_f) (Km/Hr)	84	67	73	86	63	75	80	65	70
Jam density (K_j) (DPCU/Km)	135	120	180	142	137	170	146	130	174
Capacity (Q_{max}) (DPCU/Hr)	2835	2010	3304	3053	2167	3202	2920	2113	3062

different classes of vehicles operating in the ML, KL, and RW are shown in Table 2.

The mean speed maintained by vehicles in ML was found to be more than that in the KL. The variation in the mean speed of vehicles in the ML and KL is asserted to be due to the kinematic features of the vehicle, degree of freedom of maneuverability, and driver behavior. The standard deviation (Std Dev) for each vehicle class in the ML and KL showed considerable deviation. Additionally, the Coefficient of Variation (CV) in the ML was observed to be differing from that in the KL. This difference in speed implies that vehicle speeds in ML and KL vary. This is because the number of free-flowing and following vehicles in ML is more relative to KL. The essence of the loose lane disciplined heterogeneous traffic on highways revealed that the 15th percentile (%ile), 50th%ile, and 85th%ile in the ML and KL differ significantly for each vehicle class. These characteristics are expected to be achieved due to the mixed features of the traffic and the associated driving complexities.

Difference in Vehicle Speeds in ML and KL

Since the sample size of each vehicle class was large (≥30), which varied from 113 (for Bi-cycles) to 22,223 (for Small-cars) for all the highways, a large size sample test, the z-test was used. The z-test was performed at a 95% confidence level to compare the mean speeds of vehicles in ML and KL and to discern if the mean speeds of vehicles for different lane positions vary significantly or not. The results of the z-test performed on the classes of vehicles are presented in Table 3, which shows that the mean vehicle speed in the ML varies from the mean vehicle speed in the KL. The z-test results show that driver behavior is considerably different in maintaining the vehicle speed in ML and KL. Since ML is the faster lane on the highways, a higher number of vehicles prefer to move faster in the ML than in the KL.

Lane-Based DPCU Estimation

Estimation of Dynamic PCU (DPCU) value for a vehicle is paramount to develop macroscopic, and microscopic traffic-flow models for the analysis of traffic capacity and measurement of the Level of Service (LoS) [23]. The DPCU values are usually assigned to vehicle types to normalize the heterogeneous traffic to a common unit base, which homogenizes it [28]. In this study, the DPCU values are calculated using the speed-area ratio method proposed by the Indo-HCM (2017) [3], which is shown in Eq. (1).

A study conducted by Faheem and Hashim [26] in Egypt and Himes and Donnell [27] in the USA on multilane divided highways showed similar results as obtained in this study. The authors used a t-test for comparing the mean speeds of vehicles on different lanes and investigated the effect of traffic lane position on mean speed and traffic behavior. These studies also concluded that the mean speed of vehicles on the different highway lanes varied significantly.

$$DPCU_i = (v_c/v_i)/(a_c/a_i) \quad (1)$$

where,

v_c = Mean speed of the CS, v_i = Mean speed of the ith subject vehicle, a_c= Physical area of the CS, a_i= Physical area of the ith subject vehicle

Since traffic flow on different lanes is influenced by the type of vehicle and composition of vehicles in the mixed traffic flow, therefore, to estimate the DPCU values, CS was selected as the base vehicle category. The extracted space mean speed data is used to compute the DPCU values in the ML, KL, and Roadway (RW). The RW represents the traffic on both ML and KL. In this analysis, the DPCU value of each vehicle group was compared with the Dynamic PCU and static PCU values reported in the Indo-HCM (2017) [3] and IRC:64 (1990) [4], respectively, which are presented in Table 4.

Table 4 shows that the estimated DPCU values for most vehicles are not similar to those recommended by the Indo-HCM (2017) DPCU values and IRC:64 (1990) static PCU values. Neither Indo-HCM (2017) nor IRC:64 (1990) differentiated the SCV and LCV category of vehicles which had different DPCU values as reported here. Further, Indo-HCM (2017) and IRC:64 (1990) recommends the same DPCU value and static PCU value, respectively, for two-axle trucks and three-axle trucks. However, this study shows that the two-axle trucks (MCV) and three-axle trucks (HCV) have considerably different DPCU values due to their different physical dimensions, maneuverability characteristics, operational capability, and vehicular efficiency. Also, the variance in the DPCU values for all these vehicles in the ML and KL was found to be due to the differences in vehicle dynamics, driver behavior, and traffic characteristics. The negligence to report these issues degrades the accuracy of the estimated capacity and the other traffic parameters. Hence, there is a requirement for a new piece of guidelines that report the lane-based PCU values for four-lane divided highways in India. The estimated DPCU values are used to homogenize the heterogeneous traffic and convert the traffic flow in vehicles per hour (veh/hr) to dynamic PCU per hour (DPCU/hr).

Lane-Based Capacity Estimation

The speed-flow-density relationship diagrams represent the traffic characteristic of an uninterrupted highway facility from a macroscopic point of view [29]. Since the field data did not provide the complete profile of the MFDs, therefore, three different single-regime traffic-flow models, namely, Greenshields Linear Model (GLM) [8], Greenberg Model (GBM) [9], and Underwood Model (UWM) [10], have been fitted to the field data. Based on the results of the goodness-of-fitness test using the coefficient of determination (R^2), the GLM was found to be the most effective one in describing the relationship between traffic speed and traffic density for all highway sections. The average of the R^2 was considered for selecting the best fit model. The average R^2 for GLM, GBM, and UWM were 0.9717, 0.9092, and 0.9470, respectively. The comparison of the three traffic-flow models' equations and the respective R^2 values are presented in Table 5.

The traffic parameters were estimated by developing the MFDs using the Greenshields Linear Model (GLM) [8]. The capacity for ML, KL, and RW was determined for those mentioned above three different methods using the GLM. The GLM is used due to its simplicity and higher accuracy in obtaining the relationship between speed and density. Additionally, GLM defines speed-density characteristics more effectively. The MFD curves were generated between the speed-density by one-degree equations and speed-flow and flow-density by two-degree equations for the traffic stream models. It considered flow to be a function of both speed and density. The fundamental equation of the traffic stream model is given in Eq. (2).

$$q = k * v \tag{2}$$

Where 'q' is the traffic flow in DPCU/Hr, 'k' is the traffic density in DPCU/Km, and 'v' is the traffic speed in Km/Hr. Subsequently, the estimated DPCU values were used for determining the traffic flow (DPCU/Hr) in the ML and KL, and RW, and eventually, the capacity was obtained.

Likewise, the Dynamic PCU and static PCU values reported by the Indo-HCM (2017) and IRC:64 (1990), respectively, are used to determine the lane-based capacity and RW capacity. Theoretical speed-density (q-k), speed-flow (v-q), and flow-density (q-k) curves were attained using the MFDs, which are illustrated in Figs. 9, 10, and 11. Table 6 shows the traffic parameters estimated using the DPCU values and static PCU values from the speed-area ratio method, Indo-HCM (2017) method, and IRC:64 (1990) method, respectively.

Results and Discussions

The capacity values estimated using the DPCU values from the adopted speed-area ratio method for ML and KL are 2835 DPCU/hr and 2010 DPCU/hr, respectively. However, by adopting the Indo-HCM (2017) suggested DPCU values for ML and KL, the capacity values resulted in 3053 DPCU/hr and 2167 DPCU/hr, respectively, while by adopting the IRC:64 (1990) suggested static PCU values for ML and KL, the capacity values resulted in 2920 DPCU/hr, and 2113 DPCU/hr, respectively. The lane-by-lane (ML and KL) capacity values were found to be overestimated by adopting the Indo-HCM (2017) DPCU values (of entire RW) and IRC:64 (1990) static PCU values (of entire RW) in comparison to the speed-area ratio method estimated lane-based DPCU values. This can be attributed due to the use of whole roadway DPCU values and static PCU values suggested by Indo-HCM (2017) and IRC:64 (1990), respectively, for the individual lanes (ML and KL) instead of using the lane-by-lane DPCU values or static PCU values for the lane-based capacity estimation. From Table 6, it can be seen that the capacity in ML and KL obtained by the Indo-HCM (2017) method is more than that obtained by the IRC:64 (1990) method. This occurred as a result of the DPCU values suggested by the Indo-HCM (2017) being slightly higher than the static PCU values suggested by IRC:64 (1990).

On the other hand, the RW capacity estimated by the speed-area ratio method was 3304 DPCU/hr. In comparison, the RW capacity estimated by Indo-HCM (2017) and IRC:64 (1990) was 3202 DPCU/hr and 3062 DPCU/hr, respectively. The RW capacity values were found to be underestimated by the Indo-HCM (2017) method and

IRC:64 (1990) method in comparison to the adopted speed-area ratio method. This underestimation can be attributed to the higher RW DPCU values of few vehicle categories, viz, MCV, HCV, MAV, and TR, estimated by the speed-area ratio method obtained from the field recorded traffic data.

However, the RW capacity estimated by the Indo-HCM (2017) method was found to be more than the RW capacity estimated by the IRC:64 (1990) method, which is due to the higher DPCU values of vehicles compared to static PCU values of vehicles. Thus, the lane-based capacity and RW capacity values estimated by the speed-area ratio method are significantly different from the Indo-HCM (2017) method and IRC:64 (1990) method.

The differences in the speed-flow-density (v-q-k) curve profiles between ML, KL and RW were also found to be interesting. By taking a comprehensive look at the traffic parameters results, it is evident that the free-flow speed and the jam density values in the ML, KL, and RW for the adopted speed-area ratio method are different from the Indo-HCM (2017) method and IRC:64 (1990) method. The free-flow speed and jam density values were higher in the ML than in the KL for all three methods. This can be reasoned due to the considerable variation in vehicle lane speeds, traffic conditions in the lanes, and the other uncertainties in the different lanes related to the diverse driving culture, vehicle dynamics, and mixed traffic characteristics.

It is of no surprise to notice that the RW v-q-k curve profiles are different from the individual lane (ML and KL) v-q-k curve profiles. A possible explanation may be due to the consideration of the different PCU values by these three methods. The variation can also be explained by the variation in the lane characteristics, vehicle characteristics, and diverse driving characteristics in each lane under the mixed traffic environment.

The results showed that vehicle lane locations on multilane highways significantly affect lane-based traffic characteristics, especially speed, which has a vital influence on lane-keeping behavior [30]. Thus, suggesting that the assumption of average capacity per lane and homogeneous lane-wise flow distribution (LFD) is not reasonably the same even for sites with non-varying LFD [21]. This is because the flow rates distribute disproportionately along highway lanes with different behavior depending on the number of lanes, traffic composition, and the prevailing traffic conditions [1]. Consequently, each lane of the multilane highway should be viewed separately for better interpretation of lane performance. The aggregation and averaging of different traffic lane characteristics should be avoided when performing traffic studies. Therefore, the speed-flow-density curves developed using the DPCU values reported in this study could be used to judge individual lane characteristics to achieve an adequate degree of accuracy rather than using Indo-HCM (2017) and IRC:64 (1990) suggested values for separate lanes.

Summary and Conclusions

This study aimed to estimate the lane-based traffic capacity of the uninterrupted highway facilities under mixed traffic in India. Traffic data related to vehicle speed and volume on six different multilane divided highway sections were collected using the IR sensor-based device. A z-test was used to determine the disparity in vehicle speeds in the ML and KL, which showed significant differences. This difference possibly proved to accurately describe and measure the vehicle speeds in each lane for traffic characteristics analysis. The lane-based and RW DPCU and static PCU for the vehicles on the uninterrupted highways were determined by three different methods (speed-area ratio method, Indo-HCM (2017) method, and IRC:64 (1990) method), and the comparison among the resultant values were presented. The results showed a considerable difference in the DPCU values estimated using the speed-area ratio method compared to the other two suggested DPCU/PCU values. The current study suggests using an indigenous measure for DPCU estimates for each traffic lane and RW.

The speed-flow-density fluctuations due to the vehicle characteristics on different lanes (ML and KL) and roadway (RW) as a whole under real-field traffic scenarios were analyzed using the MFDs based on the GLM [8] technique. Additionally, the comparisons among the speed-area ratio method and the traditionally followed Indo-HCM (2017) method and IRC-64 (1990) method reveal that the later methods overestimated the lane-based capacity in the ML and KL but underestimated the RW capacity compared to the adopted speed-area ratio method. The overestimation of the lane-based capacity in the two methods can be reasoned due to the use of the DPCU and static PCU factors corresponding to the RW instead of the lane by lane PCU factors. Further, the present study results show that the free-flow speed and the jam density values estimated from the speed-area ratio method are different from the Indo-HCM (2017) method and IRC:64 (1990) method. It is interpreted that the use of these DPCU and static PCU values may have amounted to overestimation and underestimation of traffic variables when they are homogenized, thus resulting in unwanted errors. Ultimately, this paper has studied the primary drawbacks of considering non-lane-based traffic characteristics for traffic analysis.

This study contributes to the literature by developing single-regime traffic-flow models for lane-based and RW traffic. The study captures lane-wise variations of MFDs, to account for the traffic dynamics in a mixed-traffic environment. The study's findings contribute to the conviction that differentiating the highway lanes could improve traffic characteristics modeling.

This study demonstrated that the IR sensors-based device has higher accuracy. This IR sensor device is robust in vehicle detection and classification [24, 25, 31]. This IR sensor device has multiple advantages over the conventionally used videography technique from the data collection and extraction point of view [32, 33].

The lane-based characterization of the highways helps to improve the accuracy of speed, PCU, capacity, and traffic-flow models. In addition, this study may provide constructive intuitions for developing lane-based microscopic simulation models resembling the real-field traffic data. This could contribute to the efficient control and management of highway facilities.

Limitations and Future Scope

While the results of this study support the present concerns of non-lane-based analysis of heterogeneous traffic using the GLM [8], this study can further be extended to estimate the capacity of the uninterrupted highway facilities using various other non-linear models and multi-regime models [11–14].

Analysis of traffic data underlying the congested regime of the v-q-k curves is not taken as the basis for developing the MFDs. Because the number of speed-flow-density data points collected from the field for the jamming condition was significantly lower. More traffic data will be collected in the future under congested conditions, and the corresponding v-q-k curves will be traced, followed by a detailed analysis.

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Declarations

Conflicts of interest Behalf of all the authors, the corresponding author states that there is no conflict of interest.

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